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Reprinted from the Preprint Volume for the
15th Conference on Severe Local Storms,
Feb. 22-26, 1988, Baltimore, MD, by the
American Meteorological Society, Boston, MA.

DYNAMICS OF CONVECTIVE SCALE INTERACTION

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1. INTRODUCTION

Movies made from high resolution geostationary satellite data, Bohan (1981) show that convective scale interaction (CSI), Purdom (1979), is of primary importance in determining the development and evolution of deep convection. CSI is directly associated with outflow boundaries produced by precipitating convective storms. CSI manifests itself as the merger and intersection of those outflow boundaries (arc cloud lines, Purdom (1973)) with other convective areas, lines and boundaries. Under the proper atmospheric conditions, this interaction has been observed to precede tornadic storm development, Purdom (1984, 1986). CSI is fundamental in the evolution and maintenance of deep convection; it is complex because of the continuously evolving nature of the convective environment. Until recently (Wilson and Carbone, 1984), CSI had only been observed using satellite imagery.

Purdom (1979) has previously identified a number of properties associated with arc cloud lines and the convective scale interactions of which they are an integral part.

Among them:

1) Arc cloud lines are of primary importance in the formation and maintenance of deep convection;
2) Arc cloud lines may maintain their identity for several hours after they have moved away from their parent source;
3) Deep convective development along an arc cloud line is a selective process; highly favored where two arc cloud lines intersect or where an arc cloud line moves into a pre-existing cumulus region;
4) New convective development along an arc cloud line is more favored early in the arc cloud line's life than later;
5) Under weak synoptic forcing, late in the day the majority of new storms form at arc cloud line intersection points;
6) Under strong synoptic forcing, thunderstorms interacting with arc cloud lines are favored for the production of severe weather and tornadoes.

While the above properties have proven useful from a qualitative point of view in real time forecast applications, for example the March 28, 1984 Carolinas' tornado outbreak (Purdom, 1985), a quantitative explanation of CSI has yet to be given. Results to be presented in this paper examine selected of the mesoscale dynamic and thermodynamic aspects of convective scale interaction. A simple explanation will be given to show how a meteorologist might couple sounding data with satellite observed cumulus development in the warm sector and the arc cloud line's time evolution to develop a short range forecast of expected convective intensity along an arc cloud line.

2. ARC CLOUD LINE LIFE CYCLE

Based on aircraft and satellite observations of arc cloud lines (Sinclair & Purdom, 1984, hereafter S & P), the life cycle of the arc cloud line may be categorized into three general stages. One must realize that arc cloud lines are evolving phenomena and exactly when one stage ends and the next begins is not distinct. The three stages transition one to the other, and along an arc cloud line all three may be in existence at the same time. Furthermore, no two arc cloud lines are exactly alike. This is due to differences in the character of their generation mechanisms (parent storm's intensity and life cycle) as well as convective scale interactions that occur along the arc cloud line as it evolves.

The three stages are most readily distinguished from one another by their link to their source. In the formative stage the arc cloud line is intimately connected to the parent storm and may be thought of in terms of that storm's gust front. In the mature stage the arc cloud line has moved sufficiently far away from the storm's downdraft that it may be treated as a density current. In the arc cloud line's dissipating stage, the parent storm has dissipated and new cold air production has ceased.

2.1. Arc Cloud Line Formative Stage

In its formative stage the arc cloud line is an extension of the gust frontal boundary produced by active convection. In this early portion of the arc cloud line's life, the movement of the storm and its gust front is essentially as described by Newton (1966): "This downdraft air, ... plays an important role in mechanically lifting the warm air at the intense convergence zone on its forward side, and thus continually

regenerating the updraft."

During this early stage of the arc cloud line's development the outflow is highly focused. A schematic of this stage of an arc cloud line's development is shown in Figure 1 which combines the results of the research aircraft flight (S & P) with results from the Doppler radar observations of Wakimoto (1982). Within a relatively deep density surge line (DSL), a strong cold outflow jet exists several hundred meters above the surface. During this stage, a precipitation roll may exist in the cool air near the leading edge of the DSL. The horizontal winds in the cold air behind the DSL are flowing into the DSL interface region at a greater velocity than is exhibited by the motion of the DSL interface. This was shown in the Doppler radar measurements of Wakimoto (1982), and may be inferred from the work of Gurka (1974) in which he showed that with active deep convection along (or very close to) an arc cloud, that the velocity of reported surface winds could be as high as twice the speed of motion of the arc cloud line. This strong relative flow in the cold air behind the DSL leads to convergence of high momentum air into the rear of the DSL interface, this convergence along with the development of a solenoidal circulation and possible dynamic pressure forces lead to strong vertical motions within that negatively buoyant air. The lifting of warm environmental air by the cold outflow air, as well as possible dynamic pressure forces in that region, gives rise to a significant vertical motion field just ahead of the arc-line gust front. Thus as a relatively rapidly moving DSL pushes out into an "undisturbed" environment, both strong convergence and intense mixing occur along the DSL interface. This strong mixing results in the entrainment of outflow air into the warmer environmental air that is thrust upward by the forward motion of the DSL, and consequently a mixed updraft region feeding the arc cloud line, Figure 2. This mixing results in a sharp decrease in vertical motion in the updraft region, between the updraft maxima and cloud gap downdraft air: the air in that portion of the updraft is also cooler and more moist than other parts of the updraft air beneath the arc cloud.

2.2 Arc Cloud Line Mature and Dissipating Stages

As the formative stage evolves to the mature stage, the DSL becomes well established and moves out from the parent storm at a more uniform velocity than that exhibited during the formative stage. At this time in the arc cloud line's life cycle, the beginning of the mature stage, the DSL takes on the characteristics of a density current.

As the arc cloud line matures and its parent storm begins to weaken the speed of motion of the arc cloud line decreases. As the cold air source weakens the strength of the cold outflow jet decreases. This in turn decreases the convergence of cool outflow air into the rear of the DSL interface. With a decrease in convergence into the rear of the DSL, and a weakening of any solenoidal circulation present, vigorous mixing of negatively buoyant air from within the DSL interface into the arc clod line updraft region decreases. Convergence in the warm environmental air due to the outwardly moving DSL results in the generation of a warm and moist positively buoyant

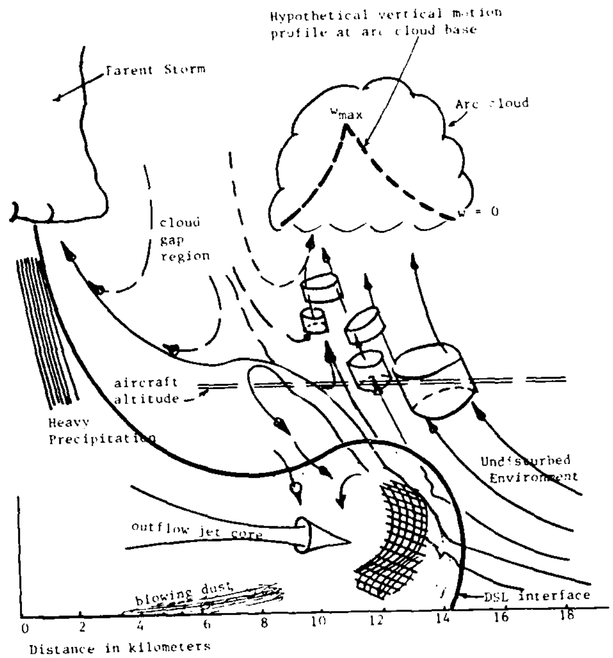

Figure 1. Several of a number of possible trajectories for air entering updraft region of arc cloud during formative stage. Shaded region is area of intense mixing along DSL interface, while hatched region is possible area of precipitation roll. Convergence in the warm air due to the advancing DSL interface is on the order of 10^{-2} sec^{-1}.

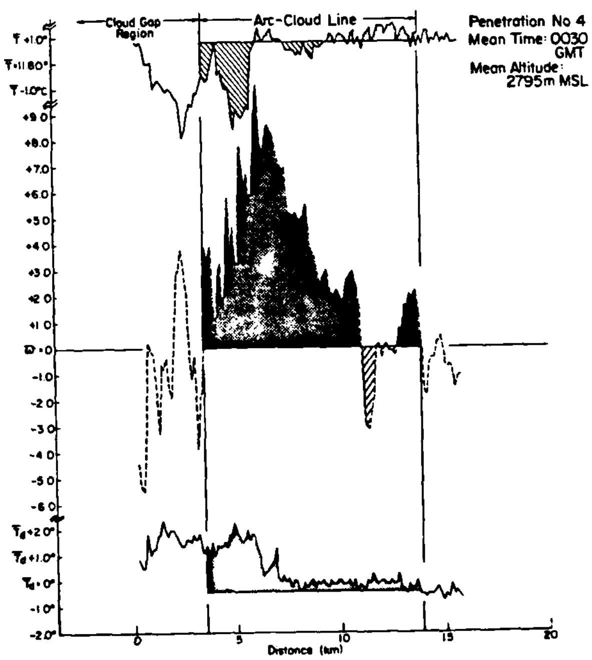

Figure 2. Aircraft data of arc cloud line penetration #4 for 12 August 1982, from Sinclair and Purdom, 1984. Values of T and T_d are in °C, and values for w are in m/s. To convert time to CST, subtract 6 hours from GMT.

updraft along the arc cloud line. The intensity and buoyant structure of this updraft region will be a function of the intensity of the arc cloud line and stability of the environment into which it is moving, as well as the less vigorously mixed outflow air that is entrained into the updraft region.

Figure 3a shows an arc cloud line over the Gulf of Mexico that is approaching Boothville, (BVE), Louisiana, while Figure 3b is a time composite image that shows that arc cloud line's evolution over a three hour time period. Notice how the amount of convection along the arc decreases the further its distance from its source region.

Fujita (1959) showed that the excess mass in the cold dome of a mesoscale high was function of the evaporation of rain inside the boundary. Fujita further showed that the total excess pressure within a cold dome whose source had dissipated, integrated over the area covered by the dome, remained virtually unchanged by subsidence as the dome spread out seeking hydrostatic equilibrium with its environment. Thus, as the arc cloud line's cold dome sinks and spreads out, the excess pressure driving the density current decreases proportionally as does the convergence along the arc as well as the depth over which that convergence occurs.

For example, assume an initial cold source with an excess pressure of 4.1 mb exists over a circular area of 50 km in radius and 1.5 km in depth. In the case of no new air being provided by an active cold air source (i.e., the parent storm has dissipated), initially the boundary will move outward at 16 m/s.* When the dome area has doubled, the excess pressure and dome depth will have decreased by a factor of 2 (i.e., p (mb) = 2.05 and DSL depth = 0.75 km), and the velocity of the boundary will be 11.3 m/s. This gives an average velocity of 13.65 m/s which means for the domes radius to spread from 50 km to 70.7 km requires an elapsed time of 25.3 minutes. Furthermore, the velocity of the boundary will have a value of approximately 35% its initial value after almost three hours. Thus, after the active cold air source has dissipated, the arc cloud line will maintain a substantial velocity for a considerable period of time. However, <u>the depth of the DSL</u> will decrease in time as the arc cloud line spreads out.

When considering the velocity of an arc cloud line during its mature stage, it should be remembered that this stage is one in which the arc cloud line's cold air source is still active. Furthermore, precipitating clouds are often found along the outflow arc. Both of those factors will contribute to a larger pressure pertubation within the cold air than for a similar situation in which the cold air source has totally dissipated. For example, for the same initial situation hypothesized above, rather than have the source totally dissipate at the initial time, let the excess pressure in the cold dome uniformly decrease by 20% (thus it is 80% of its initial value) by the time the dome area has doubled in size. This corresponds to a decrease in cold air production by the parent source of 40% from the initial time to the doubling time. By the time the cold dome has doubled in area both its excess pressure and depth have a value that is 80% of their initial value (i.e., p(mb) = 3.28 and DSL depth = 1.2 km), and the velocity of the boundary will be 15.2 m/s.

For comparison purposes, both examples given above attain a radius of 100 km in approximately one hour, however, the active source's DSL has a velocity 1.6 times as great as that for the dissipated source, and its dome is slightly over 2.5 times as deep. Such a marked differences, due to a cold source staying active, have a profound influence on the vertical motions capable of being generated in depth at the leading edge of the DSL

All calculations for velocity use the modified formula for the speed of motion of a density current given by Seiter (1983) where k was set to 0.79.

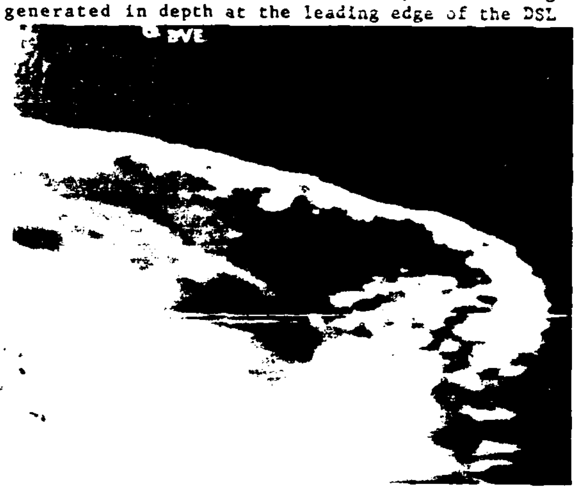

Figure 3a. GOES-East 1 km resolution visible image for July 28, 1986. The arc cloud line in the image has been produced by a large thunderstorm system that is moving slowly westward across the southern Gulf Coastal States. The arc cloud line is moving from south to north toward the Louisiana Coast.

Figure 3b. GOES-East 1 km resolution visible image time composite for 2 1/2 hours. When the arc cloud line passed Boothville (BVE), winds shifted from light northerly to south by south-westerly at 5 to 7 m/s.

due to forced convergence. Thus there is hope that by knowing the intensity of the arc cloud line's parent source and how that intensity is changing in time, coupled with direct measurements of the arc cloud line's velocity, one could define the strength of the vertical motion field being generated in the convergence zone along the leading edge of the arc cloud line.

Both satellite image and sounding observations show that marked variations in the atmosphere's ability to support deep convection exist. In the next section, local scale differences in the air mass into which an arc cloud lines advances will be investigated. By understanding those differences, and the characteristics of the arc cloud lines discussed in this section, it will be possible to explain why new deep convection is favored along an arc cloud line in one location and not in another.

3. THE AIR IN ADVANCE OF AN ARC CLOUD LINE

Satellite observations of convective scale interaction show that differences in the cloud character of the air in advance of an arc cloud line are of manifest importance to the development of new deep convective activity.

In a satellite image, the organized convective and clear regions in the air in advance of the arc cloud line reflect certain dynamic and thermodynamic features of the airmass. Pre-existing convergence and vertical motion coupled with deep layer moistening in the cumulus regions, versus gradual subsidence in the clear regions, makes the cumulus regions more favorable for deep convective development if vertical forcing takes place. How may this be quantified? Present technology does not allow the direct measurement of convergence and vertical motion on local scales over large areas. However, certain information concerning the atmosphere's ability to utilize local scale forcing for the development of deep convection are detectable using satellite sounding data.

Based on analyses of VAS satellite soundings, Zehr (1986) has shown striking differences between airmasses on the mesoscale. Those soundings contain information on the atmosphere's thermal and moisture characteristics at a spatial and temporal resolution never before available. Purdom (1985) has shown how adjacent satellite soundings may be used to assess a local airmasses ability to support deep convection. Based on considerations of parcel buoyant energy, one may calculate a variety of parameters related to thunderstorm development and intensity. For example:

1) Positive Buoyant Energy;
2) Negative Buoyant Energy, surface to lifting condensation level (LCL);
3) Negative Buoyant Energy, LCL to LFC.

One may assume that air in a convective cloudy region reflects the local scale dynamics of that region, and consequently has already had sufficient energy input to reach its LCL. Furthermore, depending on the amount of cumulus development (cumulus to towering cumulus) some portion of the input energy required to attain free convection has also been realized. In the clear regions, on the other hand, energy input is still required for the first stages of cumulus development.

Through the combined use of satellite image and sounding data it appears is possible to assess the convective potential of different portions of a mesoscale airmass, and calculate the amount of vertical forcing that must be applied to attain free convection. In the next section, information from this section and the previous section will be combined to help explain the convective scale interaction phenomena.

4. CONVECTIVE SCALE INTERACTION

The previous two sections of this paper have briefly explored the life cycle and dynamics of the arc cloud line as well as differences in the thermodynamic characteristics of the air into which it advances. That information will now be used to bring into sharper focus specific properties of convective scale interaction.

Property #1

Thunderstorm outflow boundaries may maintain their identity as arc cloud lines for several hours after they have moved away from their parent source.

In the undisturbed convective environment, in advance of the arc cloud line, small buoyant thermals rise from the surface boundary layer and rapidly mix with the surrounding environment. Because of their size and lack of organization and rapid mixing, they are unable to sustain an updraft core and in most cases never reach the condensation level; a few may produce short-lived fair weather cumulus. However, as the outflow moves away from its parent thunderstorm, lifting occurs, creating a new local environment in the vicinity of the density surge line. This new local environment is much more favorable for the growth of convective elements because of its organization, size and stronger vertical motion field. Thus, the lifting of the relatively warm, moist environmental air by the leading edge of the outflow leads to the development of a warm buoyant updraft above the DSL which initiates the development of the arc cloud line, Figure 4. For the arc cloud line to maintain its identify for several hours requires that its parent energy source provide a continuous outflow of cold air for maintenance of both the DSL's depth and field of vertical motion. Furthermore, rain showers are observed beneath some of the cumulus congestus along the arc cloud lines. This precipitation/evaporation process, and the production of new negatively buoyant air behind the arc cloud line is important in maintaining its strength, and the ensuing regeneration of convective clouds along arc cloud lines.

Property #2

The arc cloud line outflow boundary can, and often does, cause deep convection to develop along it at distances well over 150 km from its point of generation.

The ability of an arc cloud line to trigger new and vigorous convective development is a function of both the strength of the vertical motion generated along the leading edge of the DSL, as well as the stability of the environment

into which the DSL is advancing. DSL's whose source gradually decreases in intensity are able to produce stronger vertical motions at greater depths than those whose source decreases rapidly in intensity.

Thus, given similar local environments (same stability) into which arc cloud lines advance, the more vigorous their parent source remains, the more capable a DSL is of forcing parcels to greater vertical depths. However, it should be recognized that the vertical forcing along a mature arc cloud line's DSL is relatively weak: for example, assuming no mixing, an initial vertical motion of 3.87 m/s is only capable of overcoming a mean negative buoyancy of 1 °C at (T = 295 °C) over a vertical depth of 225 meters. Thus, for arc cloud lines to be such a dominating an influence on deep convective development, some other factors must be taken into account. These other factors are discussed in Properties #3 and #4.

Property #3

Deep convective development along an outflow boundary is a selective process - highly favored where the arc cloud line merges with a cumulus region or intersects another boundary. When the arc cloud line moves into clear skies deep convection rarely develops.

Merger occurs when an arc cloud line moves into a region of pre-existing cumulus and cumulus congestus cloudiness and triggers new deep convective storms. The ability of an arc cloud line to trigger new vigorous convection is a function of both the strength of the vertical motion along the leading edge of the DSL, as well as the stability of the environment into which the DSL is advancing. The DSL/outflow boundary moves into the environment ahead of it with a relatively narrow and concentrated band of vertical motion occurring along its leading edge. The strength of this organized band of vertical motion generally decreases in time. Furthermore, the air mass into which an arc cloud line moves is in no way uniform in its ability to support new deep convection. Such an environment already exhibits a certain amount of convective organization. As the arc cloud line moves into a cumulus filled region, it provides a band of organized vertical motion to a relatively moist and "locally unstable" airmass, Figure 5. Thus convective scale interaction due to merger with pre-existing convection often leads to the development of new cumulonimbus which in turn reinforces the cold pool which is driving the arc cloud line DSL. On the other hand, as the arc cloud line's DSL moves into a clear region it encounters air that is stable with respect to that in a cumulus region. When the arc cloud line's DSL interacts with that air, it generally only produces cumulus cloudiness along its leading edge as in Property #1.

Property #4

As the cumulus regime evolves on a given day, and much of the cumulus field dies away, the majority of new thunderstorms are confined to arc cloud line intersection points.

Intersection is defined to occur when two arc cloud lines come into direct contact and trigger new deep convective storms. As the two arc cloud

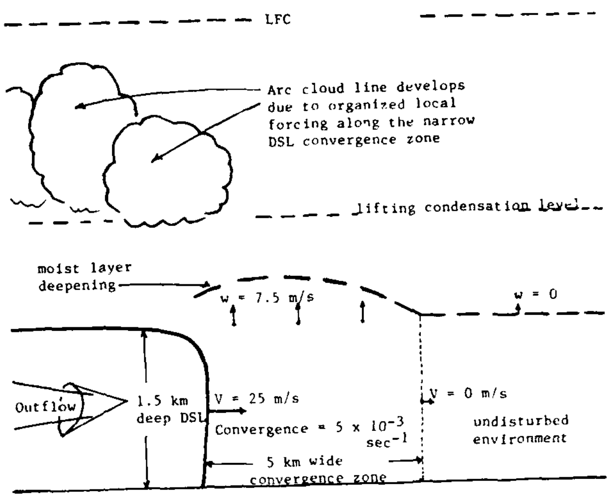

Figure 4. Schematic of convective development along an arc cloud line. The strength of of the convection that develops along the arc cloud line depends on how much of the negative buoyancy between the top of the DSL and the level of free convection (LFC) is able to be overcome by vertical motion generated in the narrow convergence zone.

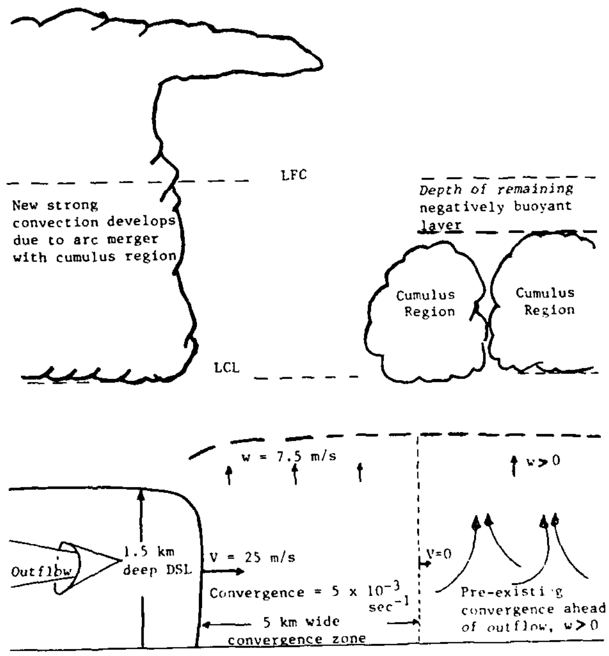

Figure 5. Schematic of strong convective development along an arc cloud line due to merger with a pre-existing cumulus region. Due to convergence in the environment ahead of the arc cloud line, a region of organized cumulus convection develops. Those cumulus represent a region where some of the vertical motion required to overcome the negative buoyancy in the environment between the lifting condensation (LCL) and level of free convection (LFC) has already been realized. Therefore, the vertical motion generated along the narrow convergence zone in advance of the arc cloud line's DSL is able to force the less stable air in the cumulus region to deep convection.

lines approach one another, increasing convergence between them results in a deeper moist layer. As two arc cloud lines intersect, a greater degree of organization and stronger forcing in the boundary layer occurs (as compared to a single arc cloud line). This causes the development of a highly organized and strong buoyant updraft at the location of the intersection. It is the formation of these highly organized and strong buoyant updrafts that lead to the development of intense thunderstorms at points of arc cloud line intersection. Since the late afternoon is a time of cumulus dissipation and stabilization, arc cloud line intersection areas naturally become the most suited regions for new deep convective development.

5. CONVECTIVE SCALE INTERACTIONS AND TORNADIC STORMS

Arc cloud lines have been associated with a number of tornado producing thunderstorms. Among the more notable, the March 28, 1984 Carolina tornado outbreak, the June 13, 1976 Chicago tornado, and the April 10, 1979 Wichita Falls tornado (examples appear in Purdom, 1984). The former two storms became tornadic after interacting with an arc cloud line boundary produced by previous convection while the arc cloud line associated with Wichita Falls storm appeared to be a product of that storm.

An hypothesis will now be presented concerning tornado genesis. First we consider the supercell case (April 10, 1979), as in Figures 6a and 6b. Referring to Figure 6a, in the pretornadic phase of the storm's mature life, all three stages of the arc cloud lines life cycle are in existence. A very deep cold air mass is generated by the storm leading to a forward flank downdraft (ffd): here the arc cloud line is in its formative stage. As the storm moves, it leaves behind a cold pool of air, the arc cloud line in its mature and dissipating stages depending on proximity to the parent storms: this cold dome is subsiding in time. New congestus grow along the arc cloud line at the right rear flank of the storm. As those congestus mature and begin to precipitate, the sinking of the cold dome to their rear, perhaps coupled with cloud boundary dynamic pressure forces (Newton, 1966), aids in injestion of mid-level dry air into the rear flank of the storm, initiating a strong rear flank doundraft (rfd). For more information on the ffd and rfd, see Lemon and Doswell, 1979. The air in the rfd is cooler than that in either the active storm's downdraft or the cold pool that the storm has left behind. Along the leading edge of the ffd a strong circulation exists due to convergence within both the cold and warm air (see DSL interface region in Figure 1) as well as a marked solenoidally driven circulation in that region. The new rfd now surges outward, intersecting the ffd, providing strong convergence and an upward thrust (tilting) of the circulation associated with the ffd into the updraft portion of the storm. This results in a rapid increase in vertical vorticity along the boundary of the mutual downdraft interaction region and tornado genesis. In a similar fashion, a strong arc cloud line (boundary) produced by earlier convection may be thought of as analgous to an ffd when that boundary is intersected by an intense mature storm that is able to move along it at a favorable angle (that is spend enough time in the region of high vorticity) tornadic activity results, as in Figure 6c.

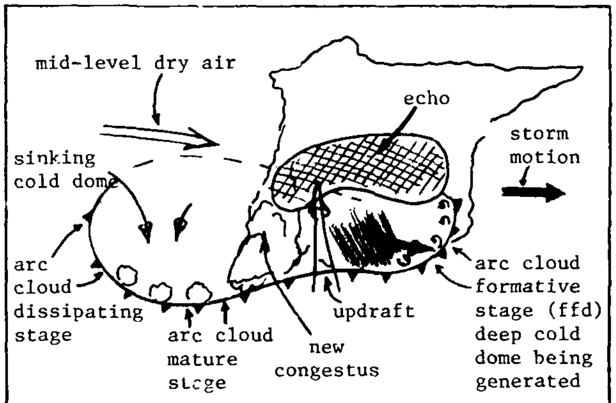

Figure 6a. Pretornadic phase.

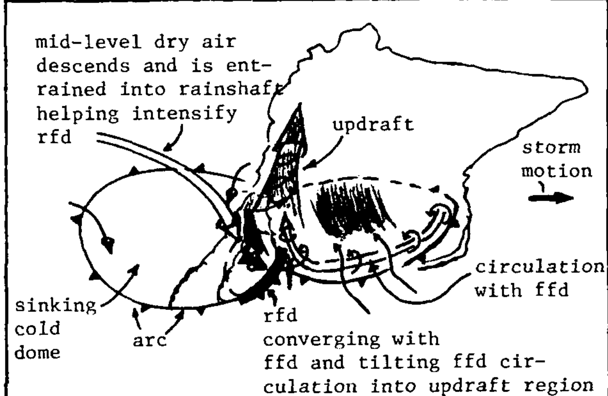

Figure 6b. Tornadic phase.

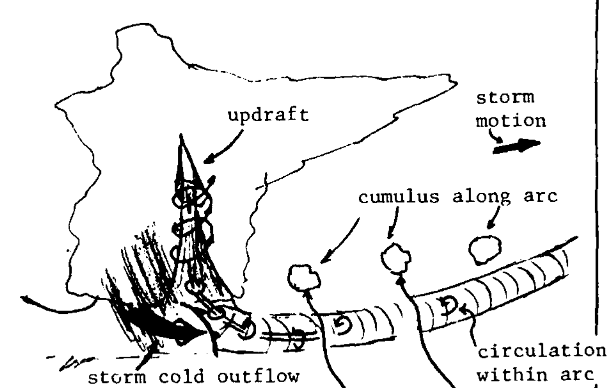

Figure 6c. Thunderstorm interacts with arc

ACKNOWLEDGMENTS

Portions of this work were supported by NSF ATM-8420980, NASA NAS8-36472, and NOAA NA85RAH 05045. The author wishes to thank Mrs. Debbie Eckdahl for help in preparation of the manuscript.

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